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FINAL REPORT ON NASA GRANT NO. NAG-8-820,

GUIDANCE TRAJECTORIES FOR

AEROASSISTED ORBITAL TRANSFER

by

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RICE UNIVERSITY

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Abstract. This paper summarizes the research on aerobraking guidance schemes performed by the Aero-Astronautics Group of Rice University during the period March 1, 1990 to December 31, 1990. The intent is to produce aerobraking guidance trajectories exhibiting many of the desirable characteristics of optimal aerobraking trajectories. Both one-control schemes and two-control schemes are studied. The research is of interest for AFE vehicles and AOT vehicles.

1.   Introduction

Current AFE and AOT guidance schemes have been under development for several years, based on previous experience with spacecraft traversing the atmosphere. For AFE and AOT flights, the major goals are: lowering the total characteristic velocity; lowering the peak heating rate; and having stability vis-a-vis dispersion effects arising because of navigation errors, variations in the atmospheric density, and uncertainties in the aerodynamic coefficients.

To achieve the above goals, certain research areas must be investigated: (i) one-control optimal trajectories; (ii) one-control guidance trajectories; (iii) two-control optimal trajectories; and (iv) two-control guidance trajectories. These research areas are important not only within the frame of AFE and AOT vehicles for near-Earth applications, but more generally within the frame of future AOT vehicles, in particular, lunar return vehicles and Mars exploration/return vehicles.

2.   Research Results

The research undertaken with the present grant has led to the publication of three Aero-Astronautics Reports (Refs. 1-3), one paper presented at the 17th Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, 1990 (Ref. 5), and four papers to appear in refereed journals (Refs. 4 and 6-8).

2D Gamma Guidance. References 1, 5, 6 deal with one-control guidance for coplanar, aeroassisted orbital transfer under the assumption that the AOT spacecraft is controlled only via the lift coefficient (hence, the angle of attack). For the atmospheric pass, a two-stage gamma guidance law is developed.

For the descending flight branch (branch 1), the gamma guidance is a linear path inclination guidance; for the ascending flight branch (branch 2), the gamma guidance is a constant path inclination guidance. The selection of the guidance parameters (entry path inclination, target altitude, switch velocity, and target path inclination) is discussed.

A modified gamma guidance is also developed. It differs from the gamma guidance in two aspects: lower target altitude; and use of a predictor-corrector algorithm to determine the switch velocity and the target path inclination. It is shown that the modified gamma guidance is quite stable with respect to dispersion effects arising from navigation errors, variations of the atmospheric density, and uncertainties in the aerodynamic coefficients (Refs. 1, 5, 6).

2D, One-Control, AOT Optimal Trajectories. References 2 and 7 deal with one-control optimal trajectories for coplanar, aeroassisted orbital transfer under the assumption that the AOT spacecraft is controlled only via the lift coefficient (hence, the angle of attack). An ideal optimal trajectory is determined analytically for lift coefficient unbounded. This trajectory is called the grazing trajectory, because the atmospheric pass is made by flying at constant altitude along the edge of the atmosphere until the excess velocity is depleted.

Starting from the grazing trajectory results, a real optimal trajectory is determined numerically for lift coefficient bounded from both below and above. It is shown that the real optimal trajectory is characterized by atmospheric penetration with the smallest possible entry angle, followed by flight at the lift coefficient lower bound. Consistently with the grazing trajectory behavior, the real optimal trajectory (nearly-grazing trajectory) minimizes the total characteristic velocity and simultaneously nearly minimizes the peak values of the altitude drop, the dynamic pressure, and the heating rate.

3D, One-Control, AFE Optimal Trajectories. Reference 4 deals with one-control optimal trajectories for nearly-planar aeroassisted orbital transfer. It is assumed that the lift coefficient (hence, the angle of attack) is kept constant and that the spacecraft is controlled via the angle of bank. It is further assumed that the entry conditions (longitude, latitude, altitude, velocity, path inclination, heading angle) are fixed.

It is shown that the optimal trajectory is a two-subarc trajectory, with the bank angle constant in each subarc (bang-bang control). The optimal values of the bank angle are $\mu = 176.7$ deg for the entry branch and $\mu = 5.5$ deg for the exit branch.

3D, Two-Control, AFE Optimal Trajectories. References 3 and 8 extend the work of Ref. 4. These papers deal with optimal trajectories for nearly-planar aeroassisted orbital transfer, the controls being the lift coefficient (hence, the angle of attack) and the angle of bank. It is assumed that the entry conditions are partly fixed (longitude, latitude, altitude, heading angle) and partly free (velocity, path inclination). Of course, the entry values of the velocity and the path inclination must satisfy a constraint arising from energy conservation and angular momentum conservation along the transfer orbit. For the atmospheric pass, both the lift coefficient and the angle of bank are optimized.

It is shown that the minimization of the total characteristic velocity is achieved by flying at constant lift coefficient and constant angle of bank, $\mu = 5.35$ deg. This result is important in that it provides the basis for simple nominal trajectories to be employed in connection with the future development of two-control guidance schemes.

3.   Abstracts of Publications

3.1. MIELE, A., and WANG, T., Gamma Guidance of Trajectories

      for Coplanar, Aeroassisted Orbital Transfer, Rice

      University, Aero-Astronautics Report No. 246, 1990.

      Abstract. This paper is concerned with the optimization and

guidance of trajectories for coplanar, aeroassisted orbital

transfer (AOT) from a high Earth orbit (HEO) to a low Earth orbit

(LEO). In particular, HEO can be a geosynchronous Earth orbit

(GEO). It is assumed that the initial and final orbits are

circular, that the gravitational field is central and is governed

by the inverse square law, and that at most three impulses are

employed, one at HEO exit, one at atmospheric exit, and one at

LEO entry. It is also assumed that, during the atmospheric pass,

the trajectory is controlled via the lift coefficient. The

presence of upper and lower bounds on the lift coefficient is

considered.

      First, optimal trajectories are computed by minimizing the

total velocity impulse (hence, the propellant consumption)

required for AOT transfer. Use is made of the sequential

gradient-restoration algorithm (SGRA) for optimal control

problems. It is shown that the optimal trajectory includes two

branches: a relatively short descending flight branch (branch 1)

and a long ascending flight branch (branch 2).

      In branch 1, the path inclination ranges from a few degrees

negative to zero and is nearly a linear function of the altitude;

in branch 2, the path inclination ranges from zero to a fraction

of a degree positive and is a slowly varying function of the
altitude. Velocity depletion takes place along the entire
atmospheric trajectory, but is concentrated mostly in the
terminal part of branch 1 and the beginning part of branch 2. As
the ratio of HEO radius to LEO radius increases, the minimum
altitude of the optimal trajectory decreases, implying that
deeper penetration into the atmosphere is required.

Next, attention is focused on guidance trajectories capable
of approximating the optimal trajectories in real time, while
retaining the essential characteristics of simplicity, ease of
implementation, and reliability. For the atmospheric pass, a
feedback control scheme is employed and·the lift coefficient is
adjusted according to a two-stage gamma guidance law. For branch
1, the gamma guidance is a linear path inclination guidance; for
branch 2, the gamma guidance is a constant path inclination
guidance. The switch from branch 1 guidance to branch 2 guidance
is governed by the requirement that a specified apogee be
reached, following the atmospheric exit. Computer simulations
show that, by proper selection of four guidance parameters (the
entry path inclination γ_0, the target altitude h_T of branch 1,
the switch velocity V_S, and the target path inclination γ_T of
branch 2), the gamma guidance trajectory can be made close to the
optimal trajectory.

Further improvements are possible via a modified gamma
guidance, which differs from the gamma guidance as follows: in
the gamma guidance, the parameters V_S, γ_T are preselected; in the
modified gamma guidance, V_S, γ_T are adjusted in flight with a

predictor-corrector algorithm; also, the target altitude of the modified gamma guidance is lower than that of the gamma guidance. Computer simulations show that the modified gamma guidance trajectory is superior to the gamma guidance trajectory in the following sense: it is more stable with respect to dispersion effects arising from navigation errors, variations of the atmospheric density, and uncertainties in the aerodynamic coefficients.

A byproduct of the studies on dispersion effects is the following design concept. For coplanar,aeroassisted orbital transfer, the lift-range-to-weight ratio appears to play a more important role than the lift-to-drag ratio. This is because the lift-range-to-weight ratio controls mainly the minimum altitude (hence, the peak heating rate) of the guidance trajectory; on the other hand, the lift-to-drag ratio controls mainly the duration of the atmospheric pass of the guidance trajectory.

3.2.   MIELE, A., WANG, T., and DEATON, A. W., <u>Properties of the Optimal Trajectories for Coplanar, Aeroassisted Orbital Transfer</u>, Rice University, Aero-Astronautics Report No. 249, 1990.

<u>Abstract</u>. This report is concerned with the optimization of trajectories for coplanar, aeroassisted orbital transfer (AOT) from a high Earth orbit (HEO) to a low Earth orbit (LEO). In particular, HEO can be a geosynchronous Earth orbit (GEO). It is assumed that the initial and final orbits are circular, that the

gravitational field is central and is governed by the inverse square law, and that two impulses are employed, one at HEO exit and one at LEO entry. During the atmospheric pass, the trajectory is controlled via the lift coefficient in such a way that the total characteristic velocity is minimized.

First, an ideal optimal trajectory is determined analytically for lift coefficient unbounded. This trajectory is called the grazing trajectory, because the atmospheric pass is made by flying at constant altitude along the edge of the atmosphere until the excess velocity is depleted. For the grazing trajectory, the lift coefficient varies in such a way that the lift, the centrifugal force due to the Earth's curvature, the weight, and the Coriolis force due to the Earth's rotation are in static balance. Also, the grazing trajectory minimizes the total characteristic velocity and simultaneously nearly minimizes the peak values of the altitude drop, the dynamic pressure, and the heating rate.

Next, starting from the grazing trajectory results, a real optimal trajectory is determined numerically for lift coefficient bounded from both below and above. This trajectory is characterized by atmospheric penetration with the smallest possible entry angle, followed by flight at the lift coefficient lower bound. Consistently with the grazing trajectory behavior, the real optimal trajectory minimizes the total characteristic velocity and simultaneously nearly minimizes the peak values of the altitude drop, the dynamic pressure, and the heating rate.

3.3.   MIELE, A., WANG, T., and DEATON, A. W., <u>Decomposition</u>
<u>Technique and Optimal Trajectories for the Aeroassisted</u>
<u>Flight Experiment</u>, Rice University, Aero-Astronautics
Report No. 250, 1990.

<u>Abstract</u>. The aeroassisted flight experiment (AFE) refers
to a spacecraft to be launched and then recovered by the space
shuttle in 1994. It simulates a transfer from a geosynchronous
Earth orbit (GEO) to a low Earth orbit (LEO). Specifically, the
AFE spacecraft is released from the space shuttle and is
accelerated by means of a solid rocket motor toward Earth, so as
to achieve atmospheric entry conditions close to those of a
spacecraft returning from GEO. Following the atmospheric pass,
the AFE spacecraft ascends to the specified LEO via an
intermediate parking Earth orbit (PEO). The final maneuver
includes rendezvous with and capture by the space shuttle. The
entry and exit orbital planes of the AFE spacecraft are identical
to the orbital plane of the space shuttle.

In this report, with reference to the AFE spacecraft, an
actual GEO-to-LEO transfer is considered and optimal trajectories
are determined by minimizing the total characteristic velocity.
The optimization is performed with respect to the time history of
the controls (angle of attack and angle of bank), with the entry
path inclination and the flight time being free. Two transfer
maneuvers are considered: (DA) direct ascent to LEO; (IA)
indirect ascent to LEO via PEO.

While the motion of the AFE spacecraft in 3D-space is described by a system of six ODEs, substantial simplifications are possible if one exploits these facts: (i) the instantaneous orbital plane is nearly identical to the initial orbital plane; (ii) the bank angle is small; and (iii) the Earth's angular velocity is relatively small. Under these assumptions, the complete system can be decoupled into two subsystems, one describing the longitudinal motion and one describing the lateral motion.

The angle of attack history, the entry path inclination, and the flight time are determined via the longitudinal motion subsystem; in this subsystem, the total characteristic velocity is minimized subject to the specified LEO requirement. The angle of bank history is determined via the lateral motion subsystem; in this subsystem, the difference between the instantaneous bank angle and a constant bank angle is minimized in the least square sense subject to the specified orbital inclination requirement.

It is shown that both the angle of attack and the angle of bank are constant. This result has considerable importance in the design of nominal trajectories to be used in the guidance of AFE and AOT vehicles.

3.4. MIELE, A., WANG, T., LEE, W. Y., and ZHAO, Z. G., Optimal Trajectories for the Aeroassisted Flight Experiment, Acta Astronautica (to appear).

Abstract. This paper deals with the determination of optimal trajectories for the aeroassisted flight experiment (AFE). The intent of this experiment is to simulate a GEO-to-LEO transfer, where GEO denotes a geosynchronous Earth orbit and LEO denotes a low Earth orbit. Specifically, the AFE spacecraft is released from the space shuttle and is accelerated by means of a solid rocket motor toward Earth, so as to achieve atmospheric entry conditions identical to those of a spacecraft returning from GEO. During the atmospheric pass, the angle of attack is kept constant, and the angle of bank is controlled in such a way that the following conditions are satisfied: (a) the atmospheric velocity depletion is such that, after exiting, the AFE spacecraft first ascends to a specified apogee and then descends to a specified perigee; and (b) the exit orbital plane is identical to the entry orbital plane. The final maneuver, not analyzed here, includes rendezvous with and capture by the space shuttle.

In this paper, the trajectories of an AFE spacecraft are analyzed in a 3D-space, employing the full system of 6 ODEs describing the atmospheric pass. The atmospheric entry conditions are given, and the atmospheric exit conditions are adjusted in such a way that requirements (a) and (b) are met, while simultaneously minimizing the total characteristic velocity, hence the propellant consumption required for orbital transfer.

Two possible transfers are considered: (IA) indirect ascent to a 178 NM perigee via a 197 NM apogee; and (DA) direct ascent

to a 178 NM apogee. For both transfers, two cases are
investigated: (i) the bank angle is continuously variable; and
(ii) the trajectory is divided into segments along which the bank
angle is constant. For case (ii), the following subcases are
studied: 2, 3, 4, and 5 segments; because the time duration of
each segment is optimized, the above subcases involve 4, 6, 8,
and 10 parameters, respectively.

It is shown that the optimal trajectories of cases (i) and
(ii) coalesce into a single trajectory: a two-subarc trajectory,
with the bank angle constant in each subarc (bang-bang control).
Specifically, the bank angle is $\mu = 176.7$ deg in the atmospheric
entry phase (positive lift projection phase) and $\mu = 5.5$ deg in
the atmospheric exit phase (negative lift projection phase). It
is also shown that, during the atmospheric pass, the peak values
of the changes of the orbital inclination and the longitude of
the ascending node are nearly zero; hence, the peak value of the
wedge angle (angle between the instantaneous orbital plane and
the initial orbital plane) is nearly zero. This means that the
motion of the spacecraft is nearly planar in inertial space.

3.5. MIELE, A., and WANG, T., <u>Near-Optimal Guidance Trajectories</u>
        <u>for Coplanar, Aeroassisted Orbital Transfer</u>, Paper No.
        ICAS-90-151, 17th Congress of the International Council of
        the Aeronautical Sciences, Stockholm, Sweden, Vol. 1,
        pp. 795-816, 1990.

Abstract. This paper is concerned with the optimization and guidance of trajectories for coplanar, aeroassisted orbital transfer (AOT) from a high Earth orbit (HEO) to a low Earth orbit (LEO). In particular, HEO can be a geosynchronous Earth orbit (GEO).

First, optimal trajectories are computed by minimizing the total velocity impulse (hence, the propellant consumption) required for AOT transfer. It is shown that the optimal trajectory includes two branches: a relatively short descending flight branch (branch 1) and a long ascending flight branch (branch 2).

Next, attention is focused on guidance trajectories. For the atmospheric pass, a feedback control scheme is employed and the lift coefficient is adjusted according to a two-stage gamma guidance law. For branch 1, the gamma guidance is a linear path inclination guidance; for branch 2, the gamma guidance is a constant path inclination guidance. The selection of the guidance parameters (entry path inclination, target altitude, switch velocity, and target path inclination) is discussed.

Further improvements are possible via a modified gamma guidance, which differs from the gamma guidance in two aspects: lower target altitude; and use of a predictor-corrector algorithm to determine the switch velocity and the target path inclination. Computer simulations show that, vis-a-vis the gamma guidance, the modified gamma guidance is more stable with respect to dispersion

effects arising from navigation errors, variations of the atmospheric density, and uncertainties in the aerodynamic coefficients.

3.6.   MIELE, A., and WANG, T., <u>Gamma Guidance of Trajectories for Coplanar, Aeroassisted Orbital Transfer</u>, Journal of Guidance, Control, and Dynamics (to appear).

<u>Abstract</u>. This paper is concerned with the optimization and guidance of trajectories for coplanar, aeroassisted orbital transfer from a high Earth orbit to a low Earth orbit.

Optimal trajectories are computed by minimizing the total velocity impulse required for orbital transfer. Each optimal trajectory includes two branches: a relatively short descending flight branch (branch 1) and a long ascending flight branch (branch 2).

Near-optimal guidance trajectories are implemented via a feedback control scheme in which the lift coefficient is adjusted according to a two-stage gamma guidance law. For branch 1, the gamma guidance is a linear path inclination guidance; for branch 2, the gamma guidance is a constant path inclination guidance.

A modified gamma guidance is developed; it differs from the gamma guidance in two aspects: lower target altitude; and use of a predictor-corrector algorithm to determine the switch velocity and the target path inclination. The modified gamma guidance is quite stable with respect to dispersion effects arising from navigation errors, variations of the atmospheric density, and uncertainties in the aerodynamic coefficients.

3.7.   MIELE, A., WANG, T., and DEATON, A. W., <u>Properties of the</u>
       <u>Optimal Trajectories for Coplanar, Aeroassisted Orbital</u>
       <u>Transfer</u>, Journal of Optimization Theory and Applications,
       Vol. 69, No. 1, pp. xxx-xxx, 1991.
       <u>Abstract</u>. See Section 3.2.

3.8.   MIELE, A., WANG, T., and DEATON, A. W., <u>Decomposition</u>
       <u>Technique and Optimal Trajectories for the Aeroassisted</u>
       <u>Flight Experiment</u>, Journal of Optimization Theory and
       Applications, Vol. 69, No. 2, pp. xxx-xxx, 1991.
       <u>Abstract</u>. See Section 3.3.

References

Reports

1. MIELE, A., and WANG, T., _Gamma Guidance of Trajectories for Coplanar, Aeroassisted Orbital Transfer_, Rice University, Aero-Astronautics Report No. 246, 1990.

2. MIELE, A., WANG, T., and DEATON, A. W., _Properties of the Optimal Trajectories for Coplanar, Aeroassisted Orbital Transfer_, Rice University, Aero-Astronautics Report No. 249, 1990.

3. MIELE, A., WANG, T., and DEATON, A. W., _Decomposition Technique and Optimal Trajectories for the Aeroassisted Flight Experiment_, Rice University, Aero-Astronautics Report No. 250, 1990.

Papers

4. MIELE, A., WANG, T., LEE, W. Y., and ZHAO, Z. G., _Optimal Trajectories for the Aeroassisted Flight Experiment_, Acta Astronautica (to appear).

5. MIELE, A., and WANG, T., _Near-Optimal Guidance Trajectories for Coplanar, Aeroassisted Orbital Transfer_, Paper No. ICAS-90-151, 17th Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, Vol. 1, pp. 795-816, 1990.

6. MIELE, A., and WANG, T., _Gamma Guidance of Trajectories for Coplanar, Aeroassisted Orbital Transfer_, Journal of Guidance, Control, and Dynamics (to appear).

7.   MIELE, A., WANG, T., and DEATON, A. W., <u>Properties of the Optimal Trajectories for Coplanar, Aeroassisted Orbital Transfer</u>, Journal of Optimization Theory and Applications, Vol. 69, No. 1, pp. xxx-xxx, 1991.

8.   MIELE, A., WANG, T., and DEATON, A. W., <u>Decomposition Technique and Optimal Trajectories for the Aeroassisted Flight Experiment</u>, Journal of Optimization Theory and Applications, Vol. 69, No. 2, pp. xxx-xxx, 1991.